

Oliver=Sharpey Lectures
ON
The Nature of Flutter and Fibrillation
of the Auricle.

*Delivered before the Royal College of Physicians of
London, April 14th, 1921.*

BY

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Oliver-Sharpey Lectures
ON
**THE NATURE OF FLUTTER AND
FIBRILLATION OF THE
AURICLE.**

LECTURE I.—AURICULAR FLUTTER.

MR. PRESIDENT,—May I first thank you, Sir, and the College which you represent for the honour you do me in appointing me to this lectureship—a lectureship founded to promote physiological research by observation and experiment and to encourage the application of physiological knowledge to the prevention and cure of disease; a lectureship founded to commemorate a great physiologist, and founded by a physician whose work in this very field is known to and admired by all of us.

The request which you have made, and which I have gratefully accepted, has come at a moment which to me is opportune. This lectureship carries with it a responsibility of no little weight; no lectureship could possess a more serious or far-seeing purpose than the welding together of Physiology and Experimental Medicine. I have said that for me the moment is opportune, for it comes at a time when observations in which I have been deeply interested for many years have grown to a state of some maturity. The observations of which I shall speak are essentially of a physiological kind; the investigations are reaching a point when their applicability to the practice of medicine cannot long remain in doubt. The subject chosen is the only subject which I could choose for these lectures—the work upon which my collaborators and myself have now been engaged for many years, a subject upon which we have been almost exclusively engaged during the past two years. These researches have comprised an attempt to solve the meaning of certain grave disturbances of the human heart beat, and it is my good fortune to be able to say to-day that we are at the end of this task.

It is a long story, and, if it is to be told intelligibly in these two lectures, it must be told connectedly. With your permission I will try and place before you the leading facts and arguments; I will narrate these, not in their historical order, but in the order most suited to my purpose, namely, to show you where our knowledge of auricular flutter and

auricular fibrillation now stands. If I am to do this in the time at our disposal I shall be unable to bring before you anything but a small part of the evidence upon which our conclusions rest. Assuring you now that I shall draw no conclusion lightly nor without most closely weighing all the evidence, I must, from the force of circumstances, ask you to take much for granted. In another direction, also, and for similar reasons, I crave indulgence. It will be impossible for me suitably to bring into the compass of these lectures the names of many contributors to this

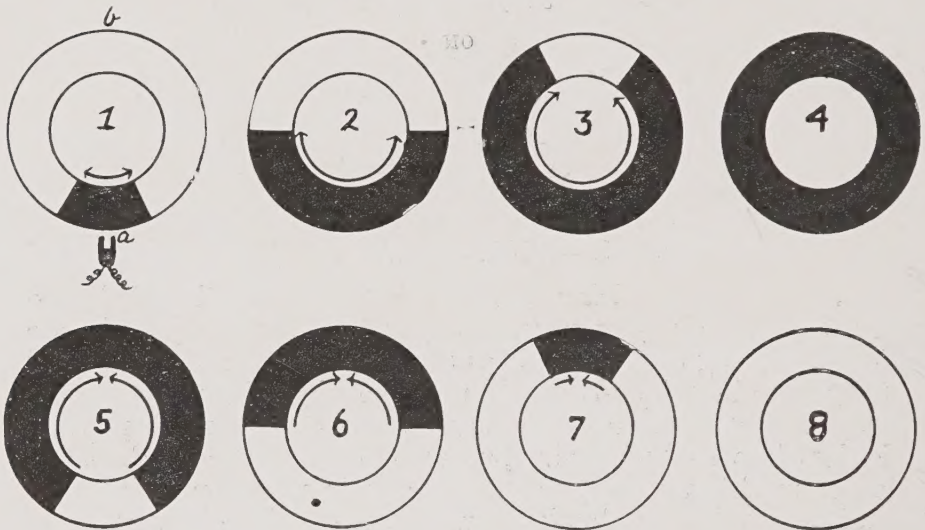


FIG. I.—A diagram illustrating the progress of a single wave passing through a ring of muscle as a result of stimulating it at *a*. The black portion of the ring represents the refractory state, and the figure shows its progress through the ring till it involves the whole (4); later the figure shows its subsidence.

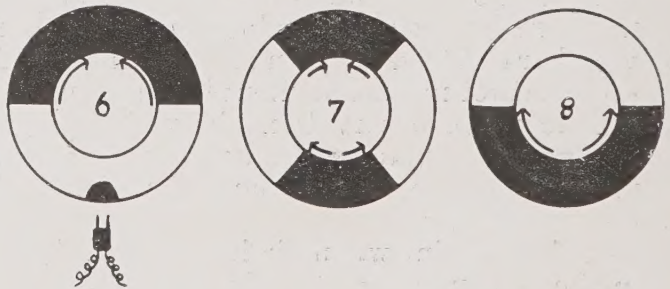


FIG. II.—A second stimulus enters the ring while it is in the condition shown in Fig. I, 6. While the first wave is subsiding the second wave spreads.

field of knowledge. This historical aspect has been dealt with recently and fully in another place. In so far as I have myself contributed during the last two years, I have contributed with my immediate collaborators; we have worked as a team under the auspices of the Medical Research Council; the names of my co-workers are Dr. Thomas Cotton and Dr. A. N. Drury of this country; Dr. H. S. Feil, Dr. W. D. Stroud, and Dr. H. A. Bulger of the United States, and Dr. C. C. Iliescu of Bucharest. From these introductory remarks I may proceed to my subject.

SOME NORMAL FEATURES OF THE CONTRACTION PROCESS.

Let me first briefly describe the relevant events when normal heart muscle contracts in response to a natural or artificial stimulus. The first event of which we possess knowledge is that it passes into what is termed the *state of excitation*. By this we mean that the muscle develops a charge, just as a battery develops a charge, and that currents flow through it and the surrounding tissues. The charge is such that the active muscle becomes relatively negative to that which is still inactive, in the sense that the zinc terminal of a copper-zinc battery is negative to the copper. These electrical changes, associated with muscular activity, are of sufficient magnitude to be recorded by means of sensitive instruments, and they yield the pictures now spoken of as electrocardiograms. The electrical change in the muscle is the immediate precursor of

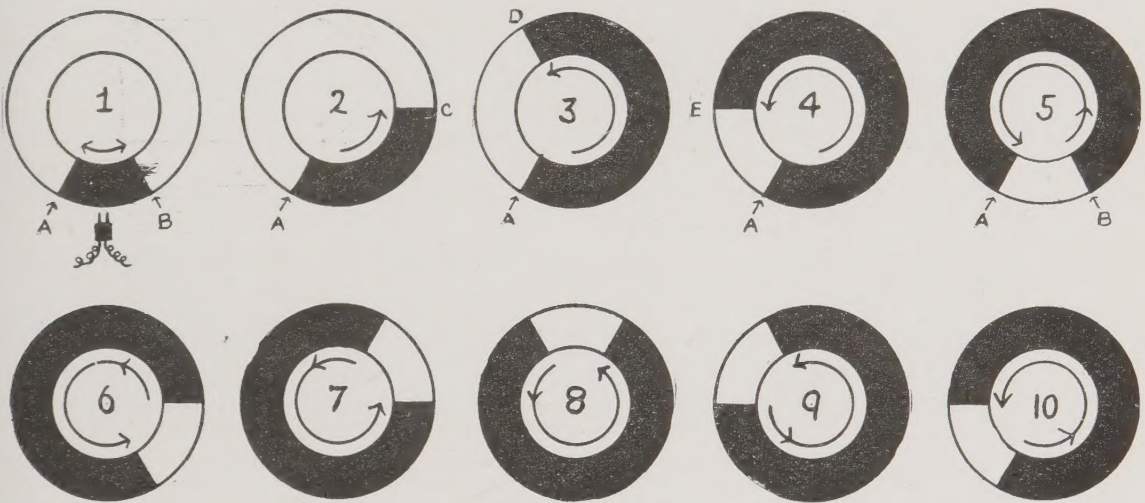


FIG. III.—A diagram to illustrate the establishment of a circus movement in a ring of muscle. The ring is stimulated in its lower quadrant and the wave spreads to *A* and to *B*. At *A* it is blocked, but from *B* it continues around the ring. When it arrives at *E* (4) the refractory state at *A* is passing, and so the wave continues to travel around the circle (5-10).

contraction :* first the muscle becomes excited (or charged), secondly it contracts. The two events are separated in the mammalian auricle by a small time interval of three-hundredths of a second or less.

Now the process of excitation is not simultaneous in all parts of the muscle; it begins at the point first stimulated and spreads from this point. Stimulate a point in the centre of a sheet of muscle and the wave spreads concentrically, as does the ripple on the surface of a pond into which a pebble is thrown. It is conducted from one muscle element to the next as a wave, which is termed the *wave of excitation*. Similarly with the contraction process itself; this also spreads as a wave which accurately follows the course travelled by the wave of excitation. It may be likened to the second ripple on the pond. For our

* That the electrical change precedes the contraction is at the moment the accepted view, though the interval is acknowledged to be very short.

present purposes and to simplify the conception, we may regard these waves as one, signalling itself as it proceeds, first electrically (first ripple), then mechanically (second ripple). When, therefore, I speak of the wave of excitation in the auricle and of the course it takes, you may picture in your minds the wave of contraction without fear of serious misconception. Nevertheless, I should, perhaps, be guilty of inaccuracy if I spoke of the wave of contraction, because our studies have been mainly, though not exclusively, directed to the wave of excitation; for movements of the latter are to be recorded with far greater accuracy than movements of the former.

Movement of the excitation wave is recorded by connecting a sensitive galvanometer directly to the surface of the muscle. As the wave passes the chosen point, the galvanometer yields a sharp deflection, and this may be

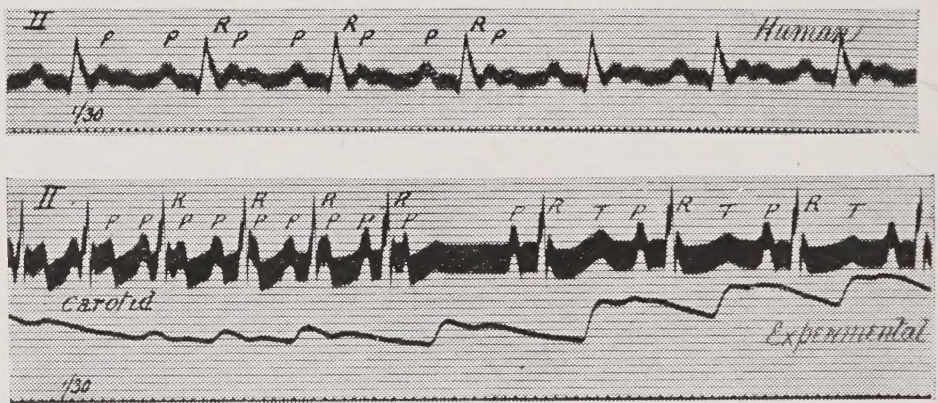


FIG. IV.—Examples of auricular flutter, clinical and experimental. The upper or clinical curve was taken from a patient in whom flutter was continuous. The auricle (*P*) is beating at a rate of 228 per minute and regularly; the ventricle (*R*) at half that rate. The ventricle responds to alternate beats of the auricle; the beat of the auricle to which there is no response falls with the beat of the ventricle. The lower or experimental curve shows the end of a period of flutter and the return of the normal rhythm. The first half of this curve is to be compared with the upper curve. During the period of flutter the auricle (*P*) is beating rapidly and regularly; the ventricle (*R*) at half the rate. The ventricle responds to alternate beats of the auricle; the beat of the auricle to which there is no response falls with the beat of the ventricle.

photographed and accurately timed against the events in some other region of the muscle. I do not propose in the present lectures to enter upon a detailed description of this delicate method, but am content to declare that we can time the arrival of this excitation wave at any point of the muscle surface with such accuracy that the error is no more, usually it is less, than one thousandth of a second; that by using two or more recording instruments simultaneously we can trace out the paths taken by waves of excitation as they travel through the muscle; and that we can estimate very accurately the time lost in the passage from point to point in different circumstances.

The wave of excitation, the first of the contraction process, travels until it involves the whole surface of the muscle; it travels in every available direction until it has

exhausted all tracts of responsive muscle. Starting in the centre it travels until it comes to the boundaries; there it ends, for at the boundary it finds no further tracts of responsive muscle through which to pass. Appropriately you may liken the spread of the excitation wave to the flame of a prairie fire. It spreads concentrically wherever it finds inflammable material; it cannot return over its scorched wake, neither can it proceed when it reaches the bounds of the dried acres. The wave of excitation leaves the muscle over which it passes in a non-inflammable, or, as it is termed, *refractory state*, and that muscle is incapable of carrying a second wave of excitation until its original inflammable state is restored. The period during which this restoration is effected is called the *refractory period* of the muscle; in the natural

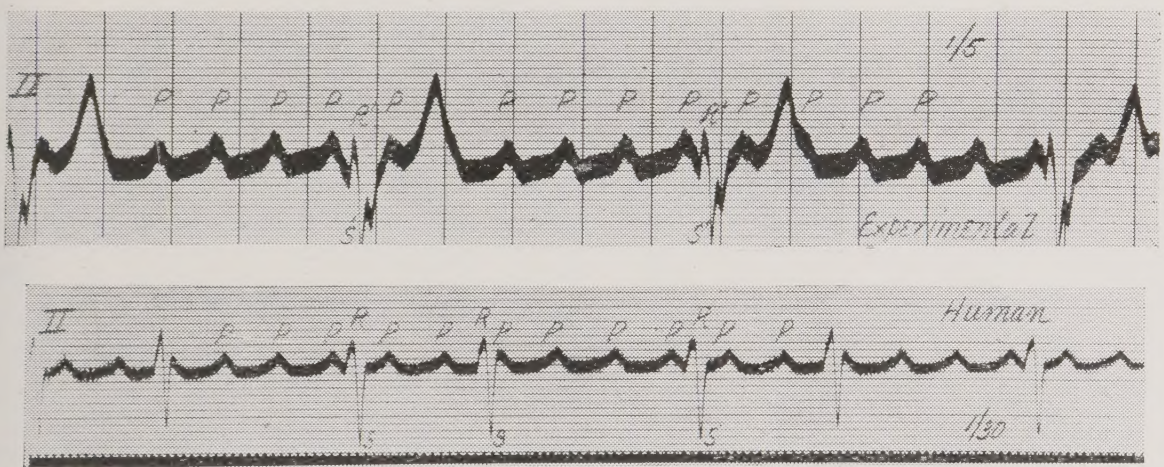


FIG. V.—Examples of auricular flutter, clinical and experimental. The upper or experimental curve was taken from a long period of experimental flutter. The auricle (*P*) is beating regularly and continuously at a rate of about 350 per minute; the ventricle (*R S*) is beating much more slowly. The lower curve is from a patient in whom flutter had persisted for many months. The auricle (*P*) is beating regularly and continuously at a rate of about 270 per minute; the ventricle (*R S*) is beating much more slowly.

beating auricle of the dog it lasts from a fifth to a tenth of a second; its duration is approximately the same as the duration of the contracted state of the muscle.

From these preliminary observations I pass to what may be termed the “ring experiment.”

THE RING EXPERIMENT.

The ring experiment was first performed by Mayer in 1908; he used the contractile bell of the jelly-fish and subsequently he utilized rings of muscle cut from the ventricles of turtles. His experiments were repeated and amplified by Mines in 1913 upon rings of muscle cut from the auricles of teleostean fishes. In 1914 both Mines and Garrey reported that they had obtained similar effects in rings of muscle cut from the dog's ventricle.

The experiment from our present standpoint is fundamental; I shall describe it, therefore, in some detail.

Suppose that we stimulate a ring of muscle, such as is depicted in Fig. I, at *a* the centre point of its lowest quadrant, and start in it by means of a single shock a wave of excitation. This wave, as soon as it has involved the whole cross section of the ring, develops two crests, which travel rapidly along the two limbs of the circle until, as shown in the serial diagrams (Fig. I, 1-4), they

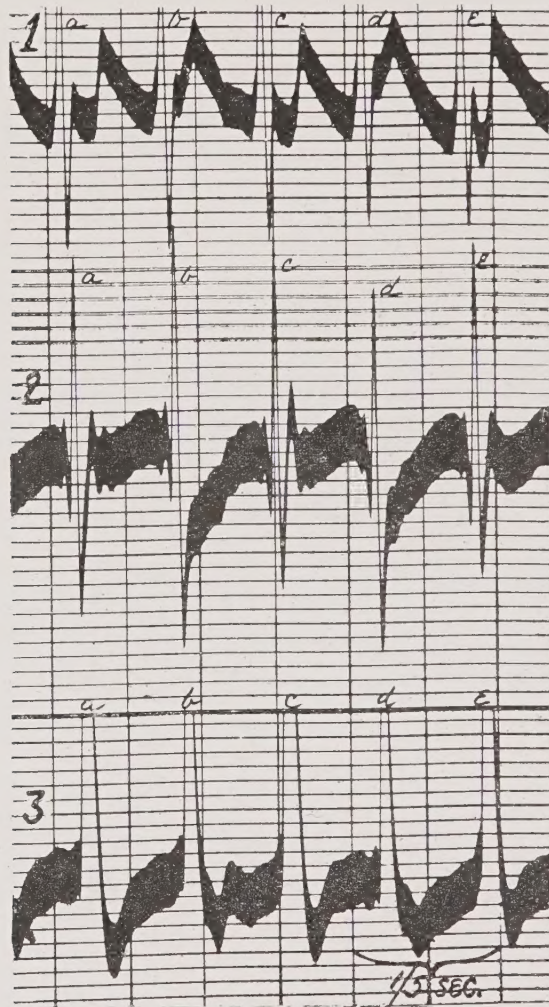


FIG. VI.—Three electrograms recorded simultaneously from the taenia terminalis of a dog while the auricle was fluttering. The top curve (1) was taken from the inferior caval, the bottom curve (3) from the superior caval, and the centre curve (2) from the mid region of the taenia. The record corresponds to five cycles of flutter (*a-e*). As each excitation wave passes, it signals itself by means of a sharp upward movement of the three recorders. Recorder 1 moves first, recorder 2 a fraction of a second later, and recorder 3 a fraction of a second later still. The order of excitation is 1, 2, and 3; the wave is passing up the taenia.

meet at point *b*, the centre point of the highest quadrant. At the instant the crests meet, the whole ring has become involved by the wave; the whole has passed into a state of excitation; it has all become "refractory." When, therefore, the two crests meet at point *b*, movement is brought to an end; like two waves of flame, two waves of excitation meeting do not override, each crest forms an impassable barrier to the other. The ring of muscle

remains in this state of excitation for a period and then recovers. It recovers in the order in which it has become involved, it begins to be "responsive" in its lowest quadrant (at *a*) first of all. The wave of "responsiveness" travels similarly as two crests along the two limbs of the ring (Fig. I, 5-8) until they also meet and coalesce at *b*, the centre of the highest quadrant. The ring of muscle

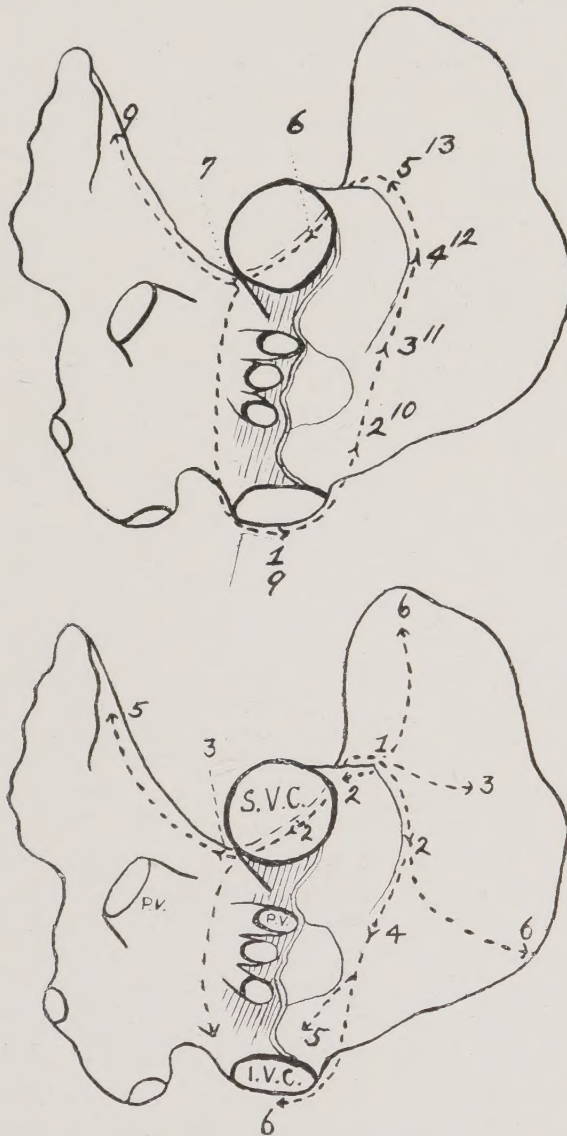


FIG. VII.—A natural outline of a dog's auricle, showing the paths of the excitation wave (broken lines) while the heart beat naturally (lower diagram) and during flutter (upper diagram). The numbers indicate the approximate order in which various parts of the musculature received the excitation wave.

has now returned to its original condition ; it is once again wholly in the responsive state.

Such is the series of events when the muscle of the ring responds to a single stimulus. If the ring is stimulated by means of slow rhythmic shocks, each shock awakens a like series of events, providing that the intervals between the shocks are amply sufficient to permit recovery. Each stimulus yields a double-crested wave of

response, which ultimately involves the whole ring. It will be evident that, if in rhythmic stimulation the second shock falls upon the ring while it is in the condition represented by Fig. I, 6, a fresh wave may be propagated at *a* before the response to the first shock has subsided at *b*. In such circumstances two waves will be moving through the ring at one time, as depicted in Fig. II, 6-8.

We come now to a different form of reaction; it is that which especially concerns us. It happens when the rate of rhythmic stimulation is raised to a critical point—namely, when the intervals between the shocks are such that each falls on the muscle at a time when responsiveness in this muscle has not wholly recovered. In such circumstances the wave propagated by stimulation may be unable to travel with its usual freedom in all directions. From time to time it is found that a wave propagated from the point of stimulation can pass in one direction only. It starts well enough, perhaps, and reaches two points of the ring *A* and *B* (Fig. III); but at *A* it finds the muscle still insufficiently responsive, while at *B* recovery is more advanced. At *A* progress comes to an end, while at *B* the crest continues to move. Suppose that at this instant stimuli are withdrawn; the conditions are peculiar. Instead of two crests, advancing to meet and interfere, there is now but one, and it is free to circulate, for as it comes to each new segment (*C*, *D*, *E*) of the ring it finds this segment excitable (Fig. III, 2 to 4). The single crested wave consequently progresses around the whole ring, and, coming back to its starting point, finds that this muscle also has recovered (Fig. III, 5); it proceeds so long as the conditions remain unaltered; it continues its course as a circulating wave which has no ending (Fig. III, 6 to 10). Thus it has been shown that, the conditions being nicely controlled, the last stimulus of a series may originate, not a single response of the ring, but an unlimited series of responses. Mines saw the wave continue to circulate for minutes, Mayer saw it continue for very many hours; this is what is meant by circus movement; it is constituted by a wave of response which travels continuously along a re-entrant path of muscle.

AURICULAR FLUTTER.

We may now examine a condition of the mammalian auricle, to-day called auricular flutter. Flutter as we now understand it was first clearly described in a patient by Hertz and Goodhart in 1909; they studied their case by means of venous curves, showing the auricle to be beating continuously and regularly at a rate of 234 per minute. Their description was quickly followed by the more ample records of Jolly and Ritchie, and of other writers. The rate of the auricular beating in flutter is from 230 to 350 per minute; the action of this chamber is remarkable, not only for its high rate, but for its regularity. It is to be recognized with the greatest certainty in electrocardio-

grams, of which examples are shown in Figs. IV and V. The condition is also remarkable because it continues uninterrupted for long periods of time. Sometimes it may occur in short paroxysms, more usually it comes to stay for months or years. Its nature until quite recently has remained altogether mysterious, though very numerous observations have indicated its close affinity to the condition called fibrillation. Thus flutter is often converted into fibrillation by the administration of digitalis. There have been few satisfactory records of a similar experimental condition. The term "flutter" was used by McWilliam as early as 1887; that was in the days when the two conditions flutter and fibrillation were not definitely distinguished. The first electrocardiograms of experimental flutter—and these curves are alone really distinctive—have been obtained during the past few years. We are now certain that a condition identical with that found clinically may be produced experimentally in the dog's auricle; this we have been taught by clinical and experimental electrocardiography.

In investigating disease there is one well known and most fruitful method of approach: it is to produce in animals a condition identical with that seen in the patient. When this has been accomplished it becomes possible to inquire into the precise nature of the disturbance. If and when that knowledge is obtained, we are in a position to consider rational plans of treatment. As I have related, in the case of flutter of the auricle, the first step has been taken. A continuous and rapid action of the dog's auricle can be produced in several ways, notably by rhythmically stimulating the organ with induction shocks at a rate of 300 to 600 per minute. The auricle is driven rhythmically and rapidly for a few seconds, and the stimuli are then abruptly withdrawn. In a certain proportion of such experiments a rapid action of the auricle continues after stimulation has ceased. The rate of action is not usually that of the rhythmic shocks which provoked it; it is usually less. For the moment our chief concern is not the method of producing this rapid and continuous action, but its nature. Its nature is variable, but amongst the after-effects of stimulation a condition identical with clinical flutter is seen from time to time. It is not every auricle which is predisposed to flutter; it is not every stimulation which will invoke flutter in the predisposed organ. That, however, is immaterial, providing that we can produce it, and can be certain when it is produced that it is identical with the clinical condition. The electrical curves, clinical and experimental (Figs. IV and V) leave us with no doubt on this subject; these curves, so delicately analytical, place the conclusion beyond question.

Having produced experimental flutter, we proceed to investigate its nature. The method of investigation consists of mapping out the path taken by the excitation wave while flutter is in progress. A single illustration of method will perhaps suffice. The auricle of a dog has

been forced into a state of flutter, as ascertained by electrocardiograms taken by methods comparable to those used clinically. The flutter continues uninterrupted. Three points are now chosen in the line of the taenia terminalis, and to each of these a sensitive galvanometric recorder is connected. The curves of these recorders write simultaneously (Fig. VI). As the excitation waves flow through the muscle they pass beneath the several contact points, and at each the passage is signalled. The curves, considered together, show that each wave is passing regularly up the taenia from the region of the inferior to the region of the superior cava, and we are able to measure the rate at which it is travelling. This record is published to illustrate the orderly character of the events as the cycles are repeated, and to indicate with what certainty the direction taken by the excitation may be ascertained. Actually a slightly different plan of campaign to that described is usually adopted. It consists of maintaining one lead as a standard and moving a second to various points of the auricle, timing the arrival of the excitation wave at its several parts relative to the standard lead, and finally of its arrival at the several parts relative to each other. To exemplify in a simplified fashion a complete experiment I may use Fig. VII. This figure shows the natural outline of the auricle as it is seen from above. The two appendices project upwards in the diagram; the superior and inferior venae cavae are represented as transected. The figures 1, 2 and 4 in the lower diagram lie on the taenia terminalis. The order of excitation displayed by this animal while the heart beats normally is indicated in the lower diagram by the figures 1, 2, 3, 4, etc. The excitation wave, as is usual when the heart beats normally, starts in the region of 1, the point at which the sino-auricular node or "pace-maker" lies. A little later it is to be found simultaneously at the points marked 2. Follow the numerals and you perceive the course which it takes. It flows simultaneously along the muscular paths which radiate from the region of the node. Thus, it flows down the taenia to the inferior cava; it flows from the base to the tip of the right appendix; it flows through the intra-auricular band to the left auricle, and, still flying from its point of origin, traverses the left appendix from its base to its tip. The wave is not visible as a wave; it travels too fast for that; the whole process of spread occupies the twentieth part of a second.

In the top diagram of the figure is the essential part of the map for the same auricle in a state of rapid flutter. The order of excitation is quite different. The wave is first traced at the inferior vena cava (1) and it passes up the whole length of the taenia (2, 3, 4, and 5). Reaching the top of the taenia it moves around the superior cava and flows through the intra-auricular band (6 and 7) to reach the left auricle. It reaches the left appendix (9), and at the same instant a wave is timed to emerge from the inferior vena cava (9). The question which at once arises is whether this second wave, emerging from the

inferior cava and repeating the course (10, 11, 12, 13, etc.) of the first wave, is a new wave or whether it is the continuation of the old one. Is there a succession of regular waves, each arising *de novo* in the inferior cava, or is there a single circulating wave? This question is answered by two considerations. If we propagate a wave artificially from the inferior cava, this spreads equal distances in equal times; it arrives at the two points 4 and 7 simultaneously. That is not the case in flutter; here it passes through point 4 to reach point 7. But the decisive argument is found in the time relation of the wave; knowing the rate at which it travels along its path (1, 2, 3, 4, 5, 6, and 7) we can calculate how long it should take to move from 7 to 9, and can compare this calculated time interval with the actual interval observed; these are found to be the same within an inconspicuous margin of error. There can be no doubt, then, that we are dealing with a wave which circulates. It circulates in this experiment around a natural ring of muscle formed by the orifices of the two venae cavae. Looked at from above, the movement is in the opposite direction to the hands of a clock. In this instance it completed one circuit in 0.16 of a second; it completed therefore 380 circuits in one minute, and that was the rate at which the auricle beat.

The experiment which I have described is one of several, but it will suffice to illustrate the kind of evidence we possess of circus movement in the auricle. Flutter consists essentially of a continuously circulating wave. The path which this central or re-entrant wave usually takes is the one I have described, but that is not invariable. Sometimes in flutter the course is different; thus, the flow may be clockwise over the same route. In other cases only one cava is encircled; the path is shorter, and the circuits are more quickly completed consequently. In other cases, though these are not so clearly evidenced, the circus movement is around other natural orifices, such as the mitral orifice. These variations are chiefly of consequence because they render the experimental work more difficult; the important conclusion is that the wave can be shown to circulate when the auricle flutters. The proof of circus movement in the auricle is not confined to the class of experiment which I have cited; there is much more evidence that I can now give you; taken as a whole I believe it to be quite conclusive.

Now the wave as a whole is not, of course, confined to the central or re-entrant path; as it passes along this path offshoots are sent through the appendices to their tips, and into all other regions of the auricular muscle. Thus the movements of the whole auricular tissue is controlled by the circulating wave. There is the central or mother-wave, and there are its centrifugal offshoots into the remaining tissue.

Such is flutter as it occurs in the dog; such, therefore, is flutter as it occurs in man. In the dog we may see flutter last for hours; in man it may last, not for hours, but for years. I have known it to continue unceasingly

for as long a period as seven years; for all we know it may continue even longer. A single wave continuously circulating for seven years: that, perhaps, may seem to be a remarkable conclusion; nevertheless, it is one we are now bound to accept.

THE FACTORS CONTROLLING FLUTTER.

We have seen that a condition comparable to clinical flutter may be produced in experiment; we have seen that when this experimental flutter is investigated it proves to consist essentially of a circulating wave. We may next consider the precise factors which maintain this circus movement. Refer back to the diagrams of the ring experiment and it will be clear that three factors are involved. They are:

1. The length of the central path.
2. The rate at which the wave travels.
3. The duration of the effective refractory period.

It must be evident that if the wave is to continue circulating a gap must exist between the crest of its advance and the wake of its retreat. As the crest travels it must always find the muscle which it enters in the responsive state. If for any reason the gap becomes closed, the wave will proceed no longer and the rapid action of the auricle will cease. The three factors named, and these alone, control the length of the gap. The duration of the refractory period at any given point must always be less than the time spent by the travelling wave in completing its circuit; this circulation time depends on the length of the path and the rate of travel. Now the rate of travel from point to point in the dog's auricle beating normally is approximately 1,000 mm. per second and the length of the refractory period at normal heart rates is approximately 0.15 to 0.2 of a second. In 0.15 to 0.2 of a second the wave will travel through 150 to 200 millimetres of muscle. On the basis of these values a circus movement could not establish itself in a ring of muscle of less than 150 to 200 millimetres circumference. But it is known that much smaller circuits than these become established. What is the reason? The reason is that when the auricle flutters, the refractory period is reduced; also the rate of travel is usually reduced. These reductions both occur in response to an increased rate of beating such as prevails in flutter. Both changes facilitate the establishment of relatively short circus movements. The precise relations of the three controlling factors have now received close investigation. They are variable in different circumstances, but may be illustrated by a type experiment. A dog's auricle is fluttering at a rate of 500 per minute. Each circuit is completed in 0.12 of a second. The circuit has a length of 60 millimetres. The rate of travel is not 1,000 millimetres per second, but 500 millimetres per second. The rate of travel is but one-half the natural rate; that is so because

the rate of beating is so high that the muscle is hard put to it to conduct the impulses. The length of the effective refractory period is not 0.20 but 0.10 of a second; it has become reduced with the rise of heart rate. The cycle is divided into two parts, a refractory phase of a tenth of a second, a responsive phase of a fiftieth of a second. The crest of the wave is constantly but a fiftieth of a second behind its own wake; it travels behind it at a distance of only 10 millimetres. We have direct and conclusive evidence that these figures may be taken as usually representative of the gap which exists; it is a minute gap, yet upon its existence the continued progress of the wave absolutely depends. To the question of this all-important gap I shall return at a later stage; it is a gap which will command the attention of many workers in the near future, for upon our power to influence its length, our success in treating flutter and, as we shall see, the closely allied condition fibrillation, will very largely depend. If by any means we could close that gap we could bring flutter to an abrupt termination.

LECTURE II.—AURICULAR FIBRILLATION.

IN the first of these lectures I have endeavoured to put before you the chief conclusions which we are able to form respecting that rather rare condition auricular flutter, and have stated that flutter as it occurs in man is due to a single wave circulating continuously. In this lecture I propose to deal with the much commoner and therefore more important disorder, auricular fibrillation. Now these two conditions are very closely related, as has been recognized for some years; they are known to be related, not only because of several resemblances, but because the one not infrequently passes into the other. Thus flutter of the auricle, as I pointed out some years ago, may usually be converted into fibrillation by the administration of heavy doses of digitalis; a conversion which is made use of in the present-day therapy of flutter. We shall see presently how the two states are related, and that circus movement underlies both. To explain the interrelation it is necessary for me to expand what I have already touched upon—namely, certain reactions of the auricular muscle to increased rate of beating. We must study in more detail the change which occurs in the length of the refractory period and in the rate at which the waves travel as the rate of beating rises.

INFLUENCE OF HEART RATE ON THE REFRACTORY PHASE, ETC.

The changes are somewhat complex, and may be illustrated most clearly by means of the accompanying

diagram (Fig. VIII). To the left of the diagram is a double-headed arrow, which represents the length of the auricular cycle when the heart is beating at a normal rate. This cycle is divisible into two parts, as indicated by the two double-headed arrows which stand just to the right of the first; it is divisible into the *refractory period*, during which the auricular muscle is in the excited or contracted state, and into the *responsive period*, during which the muscle is inactive or resting. I represent the refractory period in black and the responsive period in white, and the remainder of the diagram shows, on the basis of direct

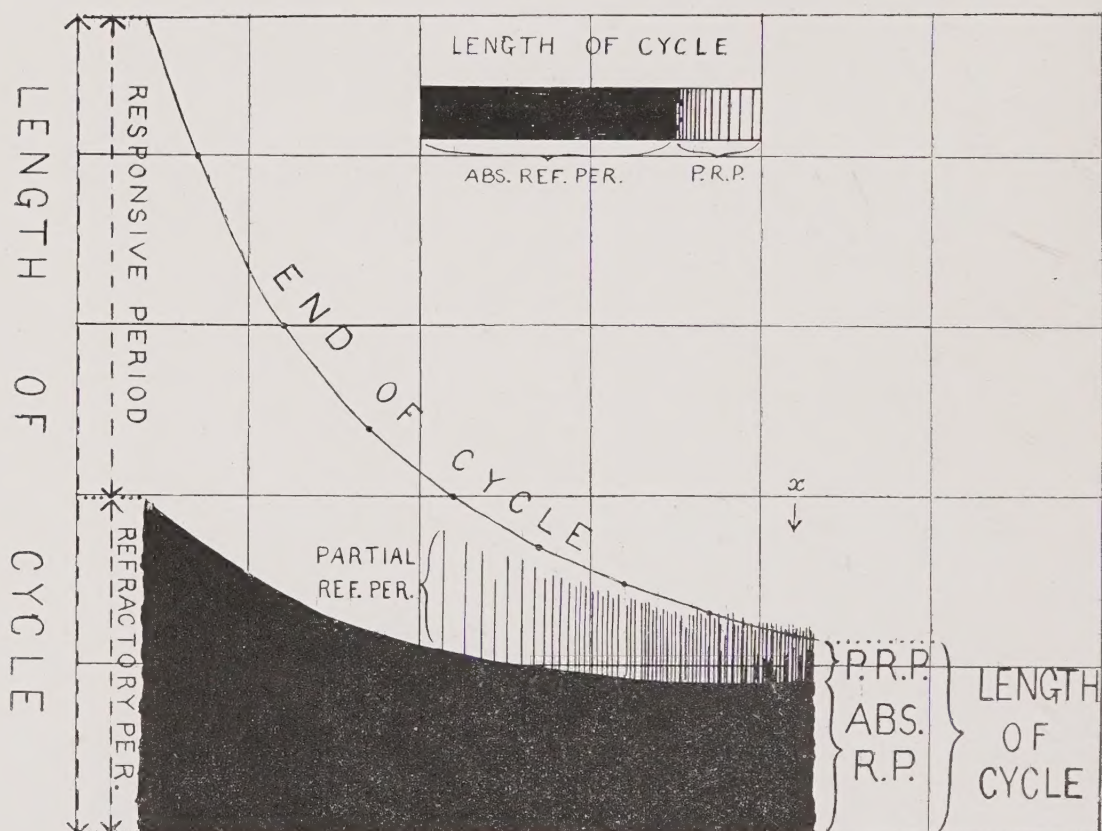


FIG. VIII.—The main diagram illustrates the relation of the refractory period to the length of the cycles when the auricular rate is raised by equal increments from its normal rate to a high level. The black portion of the diagram represents the absolute refractory period, which shortens as the rate is raised (that is, reading from left to right); a curved line indicates the shortening of the cycle itself. *P.R.P.* = period of partial refractoriness. *ABS. R.P.* = period of absolute refractoriness.

observation, how these two periods are proportioned to each other as the heart rate is raised. As the heart rate rises by equal increments—say from 100 to 150 to 200 to 250, etc.—so the length of the cycle shortens. If the lengths of the cycles, as these shorten, are charted vertically upon a horizontal base line (as in the figure), their ends join up to form a curve, the steepness of which gradually decreases. The curve of the end of the cycle approaches the base line, at first rapidly, but gradually less rapidly. The two lines will meet at infinity. The end of the refractory period also forms a curve which moves towards the base line (it is represented by the top

edge of the black portion of the figure). Briefly, the refractory period of the muscle shortens as does the length of the contraction when the heart rate is raised. But the refractory period does not shorten to the same extent as does the length of the cycle; consequently the *responsive period* dwindles when the rate is advanced. It dwindles until, eventually and at a very high rate of beating, it disappears altogether. When this happens the muscle will not respond to every impulse reaching it; it breaks into what has been termed 2:1 (or half) response—that is to say, it responds only to alternate impulses entering it. That is but natural, seeing that only alternate impulses will fall during the responsive period of preceding cycles.

Now the precise manner in which this alternating response is foreshadowed in the mammalian auricle is peculiar, and considerably important; it is necessary thoroughly to understand it. As the rate of beating rises, and the period of responsiveness shortens, a time comes when the muscle develops what is spoken of as a *partially refractory period*. It is a phase of the cycle, during which the muscle as a whole *may or may not* respond to stimulation. When this partially refractory phase first develops the cycle seems to be divisible into three parts: at the beginning is the absolutely refractory phase; this is succeeded by a partially refractory phase; a short phase remains at the very end of the cycle, during which the muscle is always responsive to stimulation. But the end of the partially refractory phase is not sharply defined; it fades imperceptibly into the phase of responsiveness. If you will, the matter may be expressed somewhat differently. During the early and greater part of the cycle the muscle is quite refractory, but the end of this phase is no longer clean cut and determinate; if at one instant the muscle is wholly refractory, at the next instant it is not wholly responsive; the refractoriness fades away gradually (through the partially refractory period) and responsiveness gradually develops. The state of refractoriness is found to be denser as it is traced backwards through the cycle until at last it becomes absolute. The development of the partially refractory phase, which is a phenomenon of high rates of beating, expedites the closure of the gap between the end of the absolute refractory period and the end of the cycle. The precise instant at which the state of partial refractoriness ends is not measurable, but it is certain that, as the rate of beating advances, it soon bridges the gap completely. When this stage is reached the cycle is divisible into two—namely, a phase of absolute refractoriness and a phase of partial refractoriness; there is no true or wholly responsive phase. This state of the muscle is represented in a small diagram above the main figure.

The meaning of the change which I have described is not obscure; it is this: when the rate is sufficiently raised, the muscle fibres do not all contract during each cycle, some contract in alternate cycles only, and the critical rate at which regular response fails is not the same for all

the muscle fibres; some fail to respond earlier than do others. During the phase of absolute refractoriness all the fibres are refractory to stimulation, during the remainder of the cycle the fibres one after another recover their excitability, the muscle as a whole becomes more and more responsive therefore, but up to the very end of the cycle some fibres still remain refractory.

I have dealt with this question of partial refractoriness at some length because it is essential that it be comprehended fully and clearly. It is a phenomenon which has fundamental influences upon the action of the auricle beating at very advanced rates. What I especially desire to emphasize is that, at these advanced rates of beating, each excitation wave entering the muscle finds that muscle imperfectly recovered from the passage of its predecessor.



IX.



X.

FIG. IX.—A schematic representation of the excitation wave as it circulates in flutter. The blackened portions of the ring represent those portions of the muscle which are refractory at a given instant. The crest of the wave travels constantly through muscle in a partially refractory state. The border of the advancing wave is finely serrated.

FIG. X.—A similar representation of the excitation wave as it circulates in fibrillation. The advancing border and retreating wake are deeply crenated, and these crenations overlap. The wave is constantly advancing through small and irregular channels of responsive tissue as these open up to receive it.

Let us apply the small diagram in the upper part of Fig. VIII to our picture of a circulating wave. In the diagrams of the ring experiment shown in the last lecture I represented the circulating wave in its most simple form. The relations there shown between the advancing crest of the wave and its wake of retreat represent what is occasionally found in actual experiment. More usually, however, the relation in flutter is a little more complex. The gap between the crest and wake does not consist of wholly responsive but of partially refractory muscle (see Fig. IX). The on-moving crest encounters many fibres which are responsive; it finds some which are still refractory. These refractory fibres form minute barriers to its progress; it wends its way from side to side, passing only where it finds channels open and ready to receive it. It is as though a second prairie fire followed a first, but followed it at

a time when the vegetation formerly burnt had not fully returned to its old condition; there would be places where the cinders of the first fire still blackened the earth, and the second flame in passing would creep around the edge of these before it could go forward. These barriers, by deflecting it, render the onrushing wave sinuous in its course, and delay its progress from point to point.

I said in my first lecture that in flutter the rate at which the wave is transmitted is not usually normal, but that it is slower than normal. We have proof that this delay is not due to change in the rate of fibre conduction, but to small barriers of unrecovered (or refractory) fibres. This observation is one of no little consequence, since it much simplifies our conception of those factors which are responsible for the maintenance of circulating waves. These factors are three—namely, the length of the muscle path, the rate of propagation from point to point, and the duration of the effective refractory period. We now see that the second factor is controlled by the third. In large measure the length of the path is also controlled by the refractory phase; for, where several channels are open to the crest of the circulating wave it will take the shortest, and that is the path along which it most closely follows its own wake. In studies of flutter, and in those of fibrillation, refractory period becomes of prime importance. Its length, and especially the length and character of its partial phase, are responsible not only for the maintenance of circulating waves, but, as we shall see, for the particular form of disordered movement which the auricle assumes.

THE PRODUCTION OF EXPERIMENTAL FIBRILLATION.

It has been stated previously that a frequent first step towards knowledge comes when we produce, by experimenting upon animals, a condition identical with that seen in our patients. In so far as fibrillation of the auricle is concerned that step was taken eleven years ago. At that time a condition termed fibrillation of the auricles was well known to experimenters, and a common form of disordered heart action was recognized in patients; but neither the experimental nor the clinical condition had been examined sufficiently closely to make it clear that the two states are one and the same. This identity was proved when the electrocardiograms of the experimental and clinical conditions were submitted to close comparison by Rothberger and Winterberg and myself in 1909, and when a little later I sought and obtained the opportunity of exposing to view the heart of a horse suffering from the same malady as do our patients.

Since the time of these demonstrations the term fibrillation of the auricle has come to be used universally in describing this particular disorder of the human heart. In Fig. XI I show again electrocardiograms of the experimental and clinical conditions. Treated pictorially the curves of auricular fibrillations are, within certain limits,

variable; but exactly comparable variations are to be seen in man and animal. The variability of the picture is in large part governed by the action of the ventricles. As you are aware, the rate of the ventricular action is not always the same, neither is the degree of its irregularity in different samples of fibrillation. It is not difficult to choose from a collection of clinical curves on the one hand and experimental curves on the other hand, examples in which the resemblance is so close as to be convincing. With the details of the curves I need not now detain you, but would remind you of their most constant features.

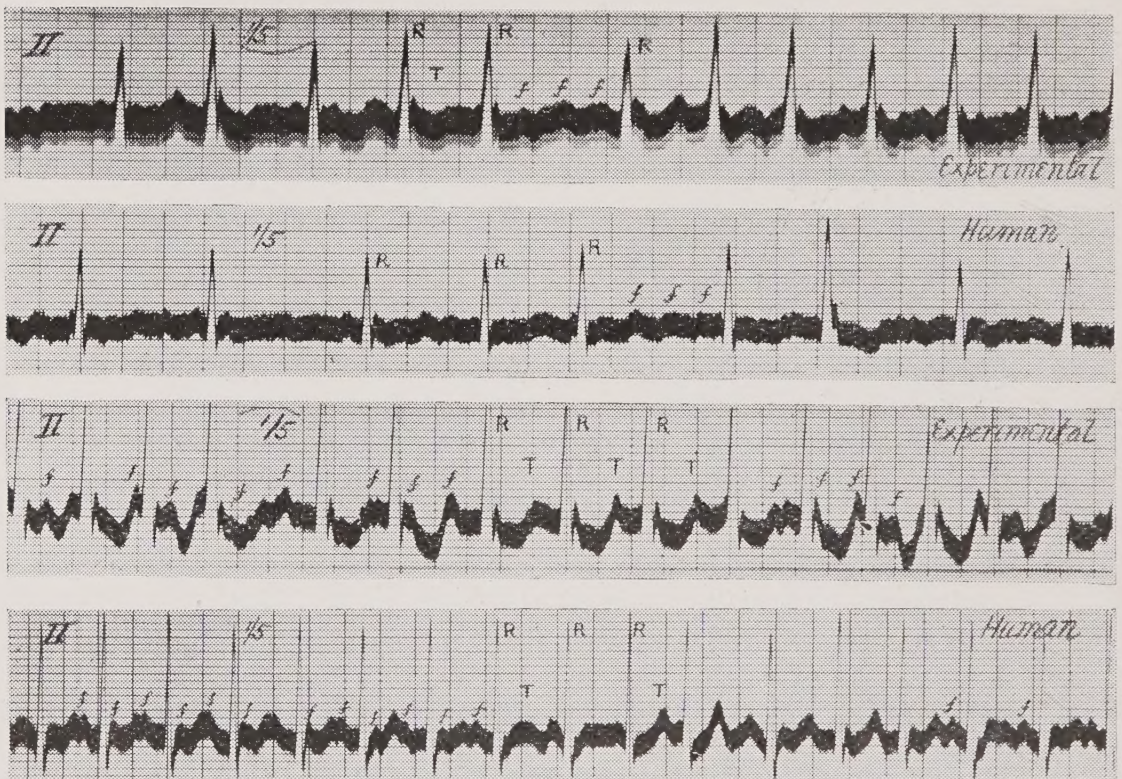


FIG. XI.—Four electrocardiograms (lead II) illustrating fibrillation of the auricles in man and the dog. The first and third curves are from dogs, and have been taken from recent experiments in which fibrillation of the auricles has been analysed. These two curves should be compared with the second and fourth respectively; these last are examples of clinical fibrillation. *R* and *T* are ventricular deflections; *ff* are the oscillations arising from the fibrillating auricles.

The ventricular representatives (*R* and *T*) are frequent and irregularly placed; the auricular representatives comprise a series of oscillations, of irregular form and somewhat irregular incidence and amplitude. The auricular representatives in flutter are united end to end; the action is quite regular and continuous, and its mean rate is approximately 300 per minute. The auricular representatives in fibrillation are not very dissimilar to these; they are also joined end to end; and the action is again continuous. The auricular action in flutter and fibrillation differs, however, in important respects; thus, in fibrillation it is 50 per cent. faster, the oscillations having a mean rate of

about 450 per minute; another difference is that in fibrillation the cycles are not accurately repeated; sometimes over short stretches of curve there may be at least a suggestion of repetition (as in the last record of Fig. XI), but close measurement will show that it is not precise; moreover, it is not long maintained. Change is the rule.

THE NATURE OF FIBRILLATION AND ITS RELATION TO FLUTTER.

I have pointed out that the first step in this inquiry was taken eleven years ago, when it was ascertained that the clinical disorder is identical with one which can be produced experimentally; but it is to be understood that we then obtained no close insight into fibrillation *quâ* fibrillation. We had obtained knowledge of a disorder of the human heart, and, more important, the means of further investigating it. It is in respect of these further investigations that I shall now speak. The method of research has been very similar to that employed in the case of flutter. We produce fibrillation of the auricles in an animal by suitable stimulation, and proceed to examine the paths taken by the excitation waves through the muscle while this fibrillation continues. It would be impossible for me to place before you in this lecture the details of this analysis; I can only attempt to acquaint you with the chief conclusions at which we arrive after fully considering the evidence derived from all sources. The main conclusion is that fibrillation, like flutter, is maintained by a circulating wave. As in flutter, the central circulating wave is a single wave, but the circuit is completed in a shorter time; the auricular cycles, therefore, follow each other more quickly. To what is this quicker movement due ultimately? It is almost certainly due to the path of the circus movement being somewhat shorter than is the case in flutter. Why should the path be shorter? Probably because in auricles predisposed to fibrillation the effective refractory period is shorter than in those predisposed to flutter. The crest of the circulating wave in both conditions tends to follow close upon its own wake. The refractory muscle forms a ring broken by a small gap; this broken ring, regarded as a whole, revolves. Now the length of refractory *tissue* in this ring at any given instant is obviously controlled by the duration of the refractory *period*. A decrease in the refractory period shortens the length of the tissue involved in this state at any given moment; consequently, if the gap remains unaltered, the diameter of the ring must shorten. If a snake glides along the path taken by its own tail, the size of the circle which it inscribes will be controlled by the length of the snake.

We believe that in fibrillation the circuit is smaller in diameter than in flutter. We cannot yet describe with confidence the precise paths which are followed; but there is some direct evidence to suggest that the mouth of

the superior cava is one of the circuits which the central wave favours. Where precisely the circuit is situated is of little moment. To recognize that a single circuit exists should suffice.

The difference between fibrillation and flutter is in part one of rate; but that is not the sole difference or even the most important difference. It has been shown to be the rule that in flutter the crest of the circulating wave is constantly passing through tissue in a partially refractory state. The wave as it progresses strikes upon small barriers which render its course finely sinuous. In fibrillation this interference is much exaggerated; the barriers sinuous. Seemingly, the crest has not a straight or simply curved border of advance; it is deeply and irregularly crenated. Its wake is similarly crenated and the crenations of the one and the other overlap and intertwine; this

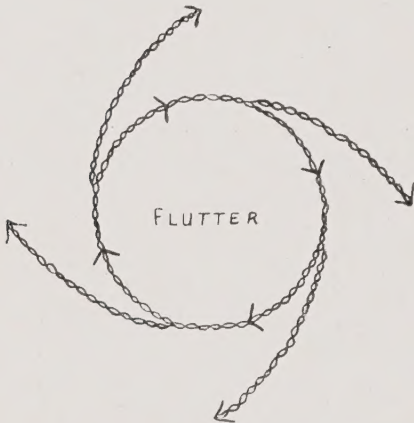


FIG. XII.—A diagram illustrating the successive paths followed by the excitation wave in flutter. The path is finely sinuous, but is in general accurately repeated from cycle to cycle.

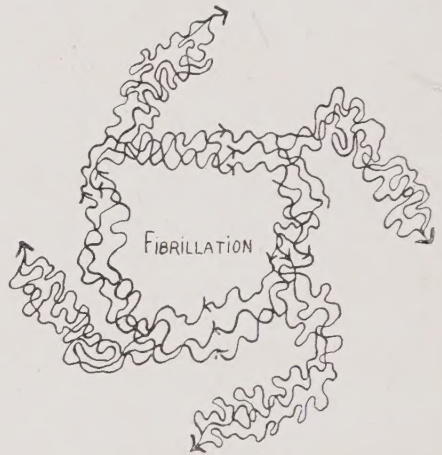


FIG. XIII.—A similar diagram of the successive paths taken in fibrillation. The path is coarsely sinuous and ever-varying, though it continues to progress in a clockwise fashion around a central area.

relation is shown diagrammatically in Fig. X. The crest of advance moves through muscle apparently in a denser state of partial refractoriness than is the case in flutter.

Picture the path travelled by the wave after it has circulated several times in flutter (Fig. XII). There is the track of the central re-entering wave; the path taken is finely sinuous, but apart from these very minor variations it is constant. As this mother wave circulates in the main channel it throws off centrifugal waves at each revolution, and these proceed into outlying areas of the muscle, such as the appendices and the sleeves of muscle on the cavæ; along these outlying channels the path is also finely sinuous, but in general constant. The whole muscle of the auricle is involved in each cycle. With each revolution the events are repeated; the waves are signalled with almost perfect regularity in every part of the musculature; at each revolution a wave passes to the region of the *A-V* node, the responses of the ventricle are, therefore, of an orderly character.

Picture similarly the path which the wave has followed after it has circulated several times in fibrillation (Fig. XIII). Everywhere the track is coarsely sinuous. There are the central tracks, spread over a wider band of tissue than in flutter,* because the path varies. Speaking very broadly, the same central path is trodden over and over again, but in detail there is no constancy. The wave may, and apparently does, encircle the same central area repeatedly if not continuously, but it staggers along its course; it is a road of many and serious obstacles. For that reason it does not return to its starting point after constant intervals of time; for that reason and because of change in the actual path pursued, the oscillations in the electrocardiograms are of irregular incidence and form. The paths through the outlying muscle also vary. Place contacts on any region of the auricular muscle, and the waves are not signalled regularly as in flutter, but irregularly; a few even fail to arrive at their proper destinations. With each irregular revolution, or at least with most, a wave passes to the region of the A-V node.† These waves arrive at the node more frequently than they do in flutter, for the general movement is somewhat faster; but because the path travelled is coarsely sinuous and variable they arrive at the node irregularly. The responses of the ventricle are therefore irregular.

THE ACTUAL CIRCUITS IN FLUTTER AND FIBRILLATION.

A single circulating wave is responsible both for flutter and for fibrillation of the auricle; in both conditions it follows the re-entrant path repeatedly, though in flutter this repetition is far more exact than it is in fibrillation. We possess some definite knowledge of the actual paths followed by the wave in the fluttering auricle of the dog. The wave may encircle the mouth of the superior cava and includes a variable amount of tissue lying between this vessel and the inferior cava; or it may encircle together the mouths of both superior and inferior venae cavae; it is probable, though it is not proven, that circuits are formed in some instances around the auriculo-ventricular orifices.

In man the rates in flutter are from 240 to 350 per minute; in the dog the rates are 345 to 580 per minute. In other words, the rates in the dog are approximately 50 per cent. faster. Difference in the size of the organ in man is sufficient to explain this difference of rate, if we assume the rate of transmission in the human and canine auricles to be equal. We may arrive at a general, if we cannot arrive at a precise, idea of the ring's circumference in the human subject. Thus, if the rate of a human flutter is 240 per minute, the duration of

* Though the band of tissue involved in successive circuits is wider, the average circle is probably of lesser diameter, as already stated. The shorter diameter is not represented in the accompanying diagram.

† The waves which reach the A-V node are approximately one-tenth less numerous than those which flow along the central path. In the average they number, therefore, about 400 per minute in human fibrillation.

each cycle is 0.25 of a second; if the rate is 350 per minute, the duration of each cycle is 0.17 of a second. Assume that the transmission rate in flutter is 500 millimetres per second, then the length of the path will be 125 millimetres in the one case and 85 millimetres in the other, and the diameters of the corresponding circles will be 4 and 2.7 centimetres respectively. Thus, if our assumed transmission rate is correct, the circular paths in flutter are of diameters somewhat exceeding the diameters of the chief orifices of the auricle. It is these natural orifices to which we look especially in attempting to locate the actual paths of the waves.

In human fibrillation the rate of movement is faster; it lies usually in the neighbourhood of 450 per minute, the cycle having a duration of 0.13 of a second. If we assume the same transmission rate, then the length of the path would be 66 mm., and the diameter of the circle would be a little more than 2 cm. It will be evident that if this estimate is approximately correct, and if we suppose the chief orifices of the auricle to be those encircled by the waves in fibrillation, that in this last condition the encirclement must be a very close one. The factor which remains in doubt is, of course, the rate of transmission.

These remarks, Sir, bring me almost to the end of what I propose to record in the present lectures. I may have been tempted to speak of possible remedies for the state of affairs which I have described, but the subject is still unripe for discussion; perhaps I have said enough in indicating what seems to me one of the chief lines which investigation should take; it is an investigation of the refractory period of heart muscle, a search for remedies which will influence the duration of this refractory state, and which, by prolonging it, will help us to close the gap between the crest and wake of the circulating wave; for this gap is essential to the maintenance of the circulating wave, whether the circulating wave is responsible for flutter or for fibrillation.

[Finally, the lecturer proceeded to demonstrate shortly his recent experiments with Dr. Drury and Dr. Iliescu upon the movements of the electrical axis of the auricle in clinical flutter and fibrillation. If suitable planes are chosen it can be shown, in both these conditions, that the electrical axis changes its direction in a definite and striking manner; it revolves through 360° as each auricular cycle is completed. As the electrical axis may be taken as an index of the general direction in which the wave is travelling, these observations demonstrate that in flutter and fibrillation the wave travels in a circular fashion through the auricle. Taken in conjunction with the experimental evidence, they constitute proof of simple circus movements in the human auricle affected by these two disorders.]

Note.—Full references to the work on flutter and fibrillation will be found in the original papers published in *Heart*, vols. vii and viii.

